

# Properties of the $D_{sJ}$ states

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**Abstract.** Recent measurements involving the newly discovered  $D_{sJ}$  particles are reported. The results of  $D_{sJ}$  production and decay branching fraction measurements are shown. Possible spin-parity and quark content assignments of  $D_{sJ}$  mesons are discussed. The results are based on a large data sample recorded by the Belle detector at the KEKB  $e^+e^-$  collider.

## 1. Introduction

A narrow  $D_{sJ}^*(2317)^+$  resonance decaying to the  $D_s\pi^0$  final state has been observed by the BaBar collaboration [1] in  $e^+e^-$  continuum interactions. Later the CLEO collaboration observed a nearby narrow  $D_{sJ}(2460)^+$  resonance decaying to the  $D_s^*\pi^0$  final state [2]. The Belle experiment has confirmed the existence of these two resonances [3, 4]. Comparing the measured  $D_{sJ}$  decay branching fractions and upper limits, the quantum numbers have been classified tentatively as  $J^P = 0^+$  for  $D_{sJ}^*(2317)^+$  and  $J^P = 1^+$  for  $D_{sJ}(2460)^+$ . However, the measured masses of these resonances are significantly lower than the values predicted within potential models for  $0^+$  and  $1^+$  states [5]. There has been a significant effort to explain the surprising  $D_{sJ}$  masses [5], and some authors have discussed the possibility of four-quark content in the  $D_{sJ}$  states. To clarify the behaviors of the  $D_{sJ}$  states the Belle collaboration has searched for  $B$  decays to two-body final states involving the combination of a  $D_{sJ}^+$  meson and a  $D$ ,  $D^*$ , kaon or pion.

## 2. $B \rightarrow \bar{D}^{(*)}D_{sJ}$ decays

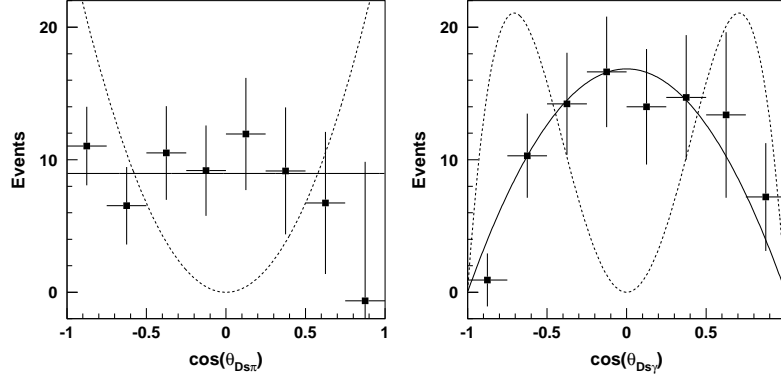
With a data sample of  $253 \text{ fb}^{-1}$  collected with the Belle detector, the  $B \rightarrow \bar{D}D_{sJ}$  decay modes are measured with improved accuracy (Belle previously published the observation of these decays with  $140 \text{ fb}^{-1}$  of data [4]) and new decay modes  $B \rightarrow \bar{D}^*D_{sJ}$  are observed. These processes are described by conventional tree diagrams, similar to the  $B \rightarrow \bar{D}^{(*)}D_s$  decays.  $D_{sJ}$  candidates are reconstructed in the modes  $D_s^{(*)}\pi^0$ ,  $D_s^{(*)}\gamma$  and  $D_s^{(*)}\pi^+\pi^-$ .

The results of the combined data fit (isospin invariance is assumed to combine decay channels) are listed in Table 1. From these measurements we obtain the branching fraction ratio:  $\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+\gamma)/\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+\pi^0) = 0.43 \pm 0.08 \pm 0.04$ .

The efficiency-corrected helicity angle [4] distributions are consistent with expectations for the  $J = 0$  hypothesis for  $D_{sJ}^*(2317) \rightarrow D_s\pi^0$  decay (Fig. 1, left) and with expectations for the  $J = 1$  hypothesis for  $D_{sJ}(2460) \rightarrow D_s\gamma$  decay (Fig. 1, right).

**Table 1.** Branching fractions and signal significances for the combined fit results.

Decay channel	$\mathcal{B}$ , $10^{-4}$	Significance
$B \rightarrow \bar{D} D_{sJ}^*(2317) [D_s \pi^0]$	$10.1 \pm 1.5 \pm 3.0$	$9.5\sigma$
$B \rightarrow \bar{D} D_{sJ}^*(2317) [D_s^* \gamma]$	$4.0^{+1.5}_{-1.4} (< 8.4)$	$3.5\sigma$
$B \rightarrow \bar{D} D_{sJ}(2460) [D_s^* \pi^0]$	$14.8^{+2.8}_{-2.5} \pm 4.4$	$8.6\sigma$
$B \rightarrow \bar{D} D_{sJ}(2460) [D_s \gamma]$	$6.4 \pm 0.8 \pm 1.9$	$11\sigma$
$B \rightarrow \bar{D} D_{sJ}(2460) [D_s^* \gamma]$	$2.6^{+1.1}_{-1.0} (< 5.7)$	$3.0\sigma$
$B \rightarrow \bar{D} D_{sJ}(2460) [D_s \pi^+ \pi^-]$	$1.0^{+0.5}_{-0.4} (< 2.3)$	$2.6\sigma$
$B \rightarrow \bar{D} D_{sJ}(2460) [D_s \pi^0]$	$0.2^{+0.7}_{-0.5} (< 1.7)$	-
$B \rightarrow \bar{D}^* D_{sJ}(2317) [D_s \pi^0]$	$3.1^{+2.1}_{-1.7} (< 8.5)$	$2.0\sigma$
$B \rightarrow \bar{D}^* D_{sJ}(2460) [D_s^* \pi^0]$	$28.7^{+7.4}_{-6.4} \pm 8.6$	$6.9\sigma$
$B \rightarrow \bar{D}^* D_{sJ}(2460) [D_s \gamma]$	$12.7^{+2.2}_{-2.0} \pm 3.8$	$10\sigma$



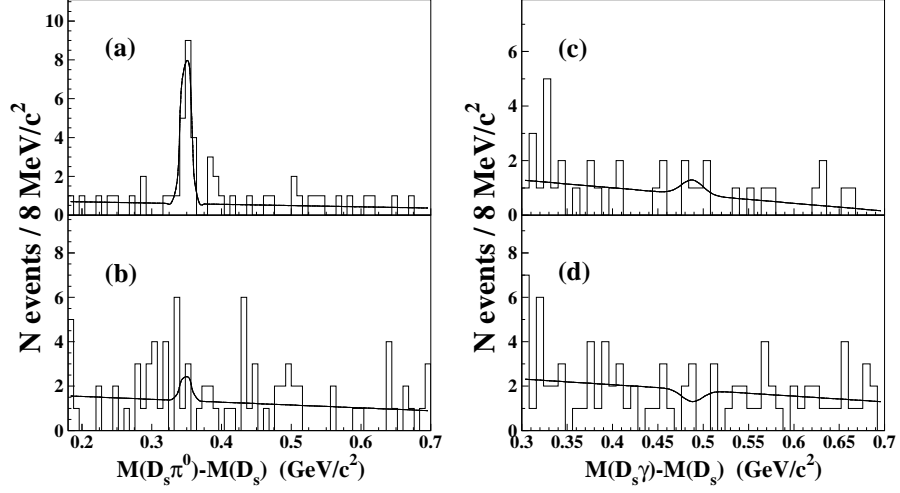
**Figure 1.** The efficiency-corrected  $\cos \theta_{\text{hel}}$  distributions for  $D_{sJ}(2317) \rightarrow D_s \pi^0$  (left) and  $D_{sJ}(2460) \rightarrow D_s \gamma$  (right) decays. Solid and dashed curves are predictions: for the  $J = 0$  and  $J = 1$  hypotheses of  $D_{sJ}^*(2317)$ ;  $J = 1$  and  $J = 2$  hypotheses of  $D_{sJ}(2460)$ , respectively.

### 3. $\bar{B}^0 \rightarrow D_{sJ}^+ K^-$ and $\bar{B}^0 \rightarrow D_{sJ}^- \pi^+$ decays

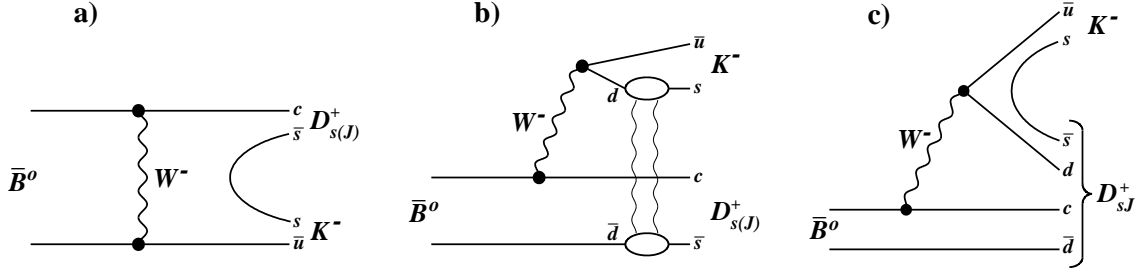
The decays  $\bar{B}^0 \rightarrow D_{sJ}^+ K^-$  and  $\bar{B}^0 \rightarrow D_{sJ}^- \pi^+$  are studied by the Belle collaboration for the first time with  $140 \text{ fb}^{-1}$  of data. The  $\Delta M(D_{sJ}) \equiv M(D_{sJ}^+ \pi^0 / \gamma) - M(D_{sJ}^+)$  distributions for the various  $D_{sJ}^+ K^-$  and  $D_{sJ}^- \pi^+$  combinations are shown in Fig. 2 for candidates from the  $B$  signal region. A clear  $\bar{B}^0 \rightarrow D_{sJ}^*(2317)^+ K^-$  signal is observed; no significant signals are observed in the remaining modes. The branching fractions, upper limits and significances for these decay channels are listed in Table 2.

The  $\bar{B}^0 \rightarrow D_{sJ}^+ K^-$  decay is generally described by the  $W$  exchange diagram (Fig. 3a) or, alternatively, the tree diagram with final state interaction (Fig. 3b). If the  $D_{sJ}$  mesons have a four-quark component, then the tree diagram with  $s\bar{s}$  pair creation (shown in Fig. 3c) may also contribute.

Assuming the approximate values of  $D_{sJ}$  decay branching fractions ( $\mathcal{B}(D_{sJ}^*(2317)^+ \rightarrow D_s^+ \pi^0) \sim 100\%$ ,  $\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma) \sim 30\%$ ), we conclude that  $\mathcal{B}(\bar{B}^0 \rightarrow D_{sJ}^*(2317)^+ K^-)$  is of the same order of magnitude as  $\mathcal{B}(\bar{B}^0 \rightarrow D_s^+ K^-)$  but at least a factor of two larger than  $\mathcal{B}(\bar{B}^0 \rightarrow D_{sJ}(2460)^+ K^-)$ .



**Figure 2.**  $\Delta M(D_{sJ})$  distributions for  $\bar{B}^0$  decays to (a)  $D_{sJ}^*(2317)^+ K^-$ , (b)  $D_{sJ}^*(2317)^- \pi^+$ , (c)  $D_{sJ}(2460)^+ K^-$  and (d)  $D_{sJ}(2460)^- \pi^+$ .



**Figure 3.** Diagrams describing  $\bar{B}^0 \rightarrow D_{sJ}^+ K^-$  decay.

**Table 2.** Branching fractions and signal significances for the  $B$  decays to  $D_{sJ}^+ K^-$  and  $D_{sJ}^- \pi^+$  final states.

Decay channel	$\mathcal{B}$ , $10^{-5}$	Significance
$\bar{B}^0 \rightarrow D_{sJ}^*(2317)^+ K^-$ [ $D_s \pi^0$ ]	$5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4$	$6.8\sigma$
$\bar{B}^0 \rightarrow D_{sJ}^*(2317)^- \pi^+$ [ $D_s \pi^0$ ]	$< 2.5$ (90% C.L.)	-
$\bar{B}^0 \rightarrow D_{sJ}(2460)^+ K^-$ [ $D_s \gamma$ ]	$< 0.94$ (90% C.L.)	-
$\bar{B}^0 \rightarrow D_{sJ}(2460)^- \pi^+$ [ $D_s \gamma$ ]	$< 0.40$ (90% C.L.)	-

#### 4. Quantum numbers of $D_{sJ}$ resonances

To determine the  $D_{sJ}$  quantum numbers, the following experimental results are considered:

- The decay mode  $D_{sJ}^*(2317)^+ \rightarrow D_s^+ \pi^0$  is dominant. No significant signals are observed for the  $D_{sJ}^*(2317)^+ \rightarrow D_s^+ \gamma$  and  $D_{sJ}^*(2317)^+ \rightarrow D_s^{*+} \pi^0$  decays.
- Significant signals are observed in the decay modes  $D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma$  and  $D_{sJ}(2460)^+ \rightarrow D_s^{*+} \pi^0$ . No significant signal is observed for the  $D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^0$  decay.
- The helicity angular distributions in the  $B \rightarrow \bar{D}^{(*)} D_{sJ}$  decays favor the  $J = 0$  hypothesis for  $D_{sJ}^*(2317)^+$  and  $J = 1$  for  $D_{sJ}(2460)^+$ .
- The helicity angular distribution in the  $\bar{B}^0 \rightarrow D_{sJ}^+ K^-$  decay favors the  $J = 0$  hypothesis for  $D_{sJ}^*(2317)^+$ .

Taking into account this information, the  $0^+$  quantum numbers for the  $D_{sJ}^*(2317)^+$  and  $1^+$  for the  $D_{sJ}(2460)^+$  are now established with high confidence.

#### 5. Quark content of $D_{sJ}$ resonances

In recent theoretical papers many authors indicate that there are no substantial reasons to assume a four-quark content (or significant admixture) for the  $D_{sJ}$  mesons. However, there are some experimental results, which can not be explained clearly within a two-quark picture:

1) The branching fraction ratio measured by the Belle collaboration in continuum:  $\mathcal{B}(D_{sJ}^*(2317)^+ \rightarrow D_s^{*+} \gamma) / \mathcal{B}((D_{sJ}^*(2317)^+ \rightarrow D_s^+ \pi^0) < 0.18$  (at 90% C.L.).

2) The branching fraction ratio  $\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-) / \mathcal{B}((D_{sJ}(2460)^+ \rightarrow D_s^{*+} \pi^0)$  is measured by the Belle collaboration to be  $0.14 \pm 0.04 \pm 0.02$  in continuum and  $< 0.13$  (at 90% C.L.) in  $B$  meson decays.

3) The branching fractions for  $B \rightarrow \bar{D}^{(*)} D_{sJ}$  measured by Belle are an order of magnitude smaller than those for  $B \rightarrow \bar{D}^{(*)} D_s$ .

4) The branching fraction for  $\bar{B}^0 \rightarrow D_{sJ}^*(2317)^+ K^-$  measured by Belle is of the same order of magnitude as that for  $\bar{B}^0 \rightarrow D_s^+ K^-$ .

In case of a conventional two-quark interpretation, the  $D_{sJ}$  decays with  $\pi^0$  in the final state must be suppressed due to isospin violation, and the ratios 1) and 2) are expected to be somewhat larger than the obtained values [6]. However, these values are readily explained within a four-quark  $D_{sJ}$  interpretation [6]. The order-of-magnitude difference in the  $B \rightarrow \bar{D}^{(*)} D_{sJ}$  and  $B \rightarrow \bar{D}^{(*)} D_s$  decay branching fractions indicated in 3) can be also explained as the effect of an additional quark pair creation in a four-quark interpretation [7]. (It has to be mentioned that, due to vector current conservation,  $B$  decay tree diagrams with a  $0^+$  meson produced from the virtual  $W$  boson are expected to be suppressed [8]; this problem was not discussed in [7].) In contrast to 3), the branching fractions indicated in 4) are of the same order, but it may be explained by the contribution from the diagram shown in Fig. 3c. Further theoretical analysis of the two- and four-quark interpretation opportunities will be required to understand the nature of the  $D_{sJ}$  mesons.

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